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Review of the PhD thesis
MSc. Kaleeswaran Balesubramaniam
„Damage localization based on piezoelectric and fiber Bragg grating sensed guided waves”

1. Base of eleboration

The basis for the review is the letter of Professor Grzegorz Żywica, Deputy Director for Scientific Issues at the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences, dated July, 28, 2023, and the attached doctoral dissertation of Mr. M.Sc. Kaleeswaran Balesubramaniam entitled "*Damage localization based on piezoelectric and fiber Bragg grating sensed guided waves*".

The work was created at Mechanics of Intelligent Structures Department of IMP PAN. The PhD student's supervisor is Dr. Hab. Paweł Malinowski and the auxiliary supervisor: Dr. Eng. Rohan Soman from Mechanics of Intelligent Structures Department.

2. Topics of work

The thesis deals with development of an effective multistep damage identification procedure using ultrasonic guided waves. The proposed procedure addreses three stages of damage identification namely detection (step 1), localization (step 2) and quantification (step 3). The individual stages of the proposed methodology can be characterized as follows:

Step 1. is utilizing simple damage indices such as Root Mean Square Deviation or Cosine Distance.
Step 2. is accomplished by employing Sectional Elliptical Method.
Step 3. is implemented with aid of Confusion Matrix determined at the pixel level.

All three steps of damage identification are current research topics and constitute an important part of the living trend of health monitoring of mechanical structures. The proposed methodology were analyzed on many examples of isotropic and anisotropic structures and took into account various types of damages. Therefore, the topic of the dissertation has significant engineering potential. Undertaking such a specific research topic should be considered fully justified.

3. Scope and content of the thesis

The dissertation has 138 pages and it was written in English. It is divided into 8 chapters and 6 appendices, ending with a list of literature. The bibliography contains 128 items, including 10 items co-authored by the PhD candidate, which are indexed in the Scopus database. Additionally, the PhD candidate published his works in renowned journals from the current list of MEiN (*Smart Materials and Structures, Measurement, Materials* and *Sensors*). He also published two chapters in the books and 12 conference papers in the prestiguous conferences devoted to SHM.

In chapter 1, serving as an introduction to the theory of waves, fundamental concepts of Structural Health Monitoring have been presented. The chapter also presents a short description of the most frequently used types of sensors ie. piezoelectric transducers and fiber Bragg gratings. Finally, the chapter contains classification of waves traveling in solid media indicating importance of Lamb waves in damage identification of plates.

Chapter 2 is devoted to a brief survey of the literature on guided waves and their application to SHM. Other aspects such as optimal sensor placement, temperature effects on guided waves and finite element modelling of wave propagation are discussed in this chapter. Finally, the last section of the 2 chapter provides information about sensing and data aquisition equipment used in this research.

Motivation and the purpose of the study have been presented in chapter 3. It is indicated that the aim of the thesis is to develop and evaluate effectiveness of multi-step method for damage identification in structures using three type of sensors, ie. Laser Doppler Vibrometer, piezoelectric transducer and fiber Bragg grating sensor. The hypothesis to be proven by PhD candidate is stated as follows: **it is possible to develop a common multi-step SHM methodology, which is able to identify damage in an accurate and reliable way using all mentioned above sensing technologies**.

In chapter 4 efficient method for damage localization is introduced. The method is called *Sectional Elliptical Method* (SEC) and its advantage is related to reduced computational time compared to original elliptical algorithm. Experimental verification of the elliptical algorithm for damage localization described in chapter 4 has been demonstrated in chapter 5. Two types of structures have been investigated. They were *Aluminium Nomex Composite Structure* (ACS) and *Glass Fiber Reinfored Polymer Structure* (GFRPS).

Chapter 6 is the most important chapter of the thesis. In this chapter PhD candidate provides details of the proposed multistep methodology and its effectiveness in detecting, localizing and quantifying different types of damages in various structures. The case studies include *Sandwich Honeycomb Composite Structure* (SCS) with multiple debonding defects, *Carbon Fiber Reinforced Polymer Structures* (CFRPS) with multiple impact damages and aluminium plate with attached magnets simulating damage.

Chapter 7 focuses on measurements of guided waves with direct and remote bonding configurations of FBG using different PZT arrangements and different bond lengths. The effect of embedding the FBG sensor into a structure has been investigated in this chapter with aid of finite element method.

In Chapter 8, which ends the dissertation, the PhD candidate briefly summarizes the obtained research results. The appendix chapter demonstrates MATLAB package dedicated to extract guided wave signals and its further processing.

4. Evaluation of the thesis

The dissertation is devoted to the multistep damage identification of plate structures, taking into account its applications in the aerospace and automotive industries. Such a research topic is currently investigated and fit well into the research direction related to modern methods of structural health monitoring.

The doctoral candidate proficiently uses the methodology of conducting scientific research in his discipline, i.e. 1) he begins his work by outlining broad issues; 2) mathematically formulates and analyzes individual tasks, discusses their variants and special cases; 3) develops numerical solution methods and verifies them on a number of representative tasks; 5) proposes and analyzes the possibility of practical implementation of the developed methodology; 6) discusses the literature background and places its results in it. This research pattern, reflected in the structure of the dissertation, confirms the scientific maturity of the PhD candidate.

The following should be considered interesting and significantly original elements of the dissertation:

- A clear and uniform systematization of the methodology for detecting, localizing and quantifying of various types of structural damages with aid of ultrasonic guided wave technology.
- Selection of an appriopriate damage index in form of Root Mean Square Deviation (RMSD) for measurment with piezoelectric sensors and Cosine Distance (CD) for fiber Bragg grating sensors.
- Development of an efficient computational algorithm in form of Sectional Elliptical Method to determine the localization of damage in the structure.
- Verification of the proposed multistep methodology on various types of isotropic and anisotropic structures.
- Finite element study of embedded Fiber Bragg Grating (FBG) sensor along with experimental analysis of direct and remote bonding of FBG sensor.

What is particularly noteworthy is the wide scope of the research conducted, which covers three different stages of damage identification (detection, localization and quantification). These topics requiring the use of various methods of numerical analysis and experimental techniques. The thematic scope and structure of the work prove the PhD student's proficiency in theoretical and experimental research work.

The dissertation is of the nature of basic research, however, the methods developed relate directly to real design problems and their application potential should be assessed as very important. This applies both to the possibility of implementing proposed damage identification methodology, as indicated in the work, as well as to checking their reliability and effectivens in various types of damages occuring in various structures.

5. General comments and questions

The reviewer did not notice any major errors or omissions in the dissertation. The following comments and questions are of a debatable nature and are intended to contribute to increasing the transparency and cognitive value of the dissertation.

- The second paragraph of abstract (page ii) starts with sentence: "*The research aims to develop an effective multistep damage identification process (detection, localization and quantification) using the proposed SHM-GW method.*" If so, why the title of the dissertation has narrower scope and starts with words "damage localization" instead of "damage identification"?
  Similar remark could be done regarding sensing techniques used in the study. In the title of dissertation there is lack of information about Laser Doppler Vibrometer (LDV).

- On page 87 one can find a description of the 3D numerical model of the aluminium plate created for simulation of wave propagation with aid of finite element method. To perform such a simulation with reasonable accuracy one has to choose small size of finite elements to capture short wavelength. Therefore, as it was noticed by Author FEM-assisted guided wave studies are time-consuming. Would it be possible to speed up such a calculation using *Graphical Processing Unit* (GPU)?

- Page 113 (Appendix A.2) starts with Table representing comparison of velocities obtained during experimental campaign (DAQR) and numerical simulation (FEM). There is a discrepancy between these two values. One question arises: Would it be possible to calibrate the FEM model in such a way that the experimental and numerical velocites are the same? If so, which parameters should be choose to achieve such an agreement?

- Figure A.13 (page 121) represents finite element mesh of the aluminium plate with circular arrangement of piezoelectric transducers. Why this FE mesh is irregular? Wouldn't it be better to use mesh generator for structured mesh (the one reflecting circular arrangement of transducers)?

- Fourth level of the SHM methodology is prediciton of the life span of the structure. Would it be possible to extend proposed methodology to prediction step, in which damage identification (steps 1, 2 and 3) would be integrated with digital twin of the tested structral component? Measurement data gathered during individual tests could train computational model which would allow to estimate remaining life of the structure.

6. Typographical errors

The dissertation is prepared in English. Its English language and composition are clear and do not require any corrections. Further comments are not of a substantive nature, but only of a technical and editorial nature.

- Equations (2.1), (2.2) and (2.3) contain an excess round bracket (which should be removed. However, sample amplitude denoted as $k_i(x,y,t)$ should be raised to the power of 2.
- Page 33, sentence "*The sector calculation aims to reduce calculation time …*" appears twice in the text.
- There is a mistake in equation (4.1). Square root is valid only for numerator. Denominator is just a velocity without square root above it.
- There is a sepelling error in Figure 4.5. "*Velocities fro …*" should be replaced with *for.*

- In page 62 it is written "*D1 (2 cm square area with centre coordinates 39 cm, 19.5 cm)*" in Figure 6.12 (page 74) this value is 2 cm x 2cm with center at 35.5 cm and 19.5 cm.
- Page 83 (Figure 6.13) replace "*Doble sided magnets*" with "Double ..."
- Page 106 (Figure 8.1) acronym HCS is not defined. Is it the same as Sandwich Honeycomb Composite Structure (SCS)?
- Page 119 (Algorithm 1) the pseudo code should be written with the indentation. There is also missing information on line 9 of the pseudo code.

7. Conclusions

Doctoral dissertation of Mr. Kaleeswaran Balasubramaniam concerns current topic in the field of structural health monitoring: efficient multistep damage identification using guided waves. In solving the research problems, the PhD candidate used the methodology of conducting scientific research and demonstrated the ability to conduct it independently. The achieved results should be considered original and interesting for the wider scientific community. The dissertation generates further research problems, which confirms its importance. The critical remarks presented in the review are of a technical nature and do not reduce the value of the work.

The reviewed dissertation is an original solution to a scientific problem and meets all the requirements for doctoral theses by the applicable Law on Higher Education and Science of July 20, 2018 (Journal of Laws 2018, item 1668).

I declare the scientific work of Mr. Kaleeswaran Balasubramaniam is suitable for the open discussion and after a successful defense I suggest giving the PhD title.